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Modeling Intermodal Freight Hub Location Decisions

Ackchai Sirikijpanichkul and Luis Ferreira

Abstract— **The paper presents an evaluation model for the location decisions of road-rail intermodal freight hub. The problem of optimizing individual freight actor's benefits is addressed in the model which comprises four different modules. Each of the modules represents a hub user, a hub owner or operator, a transport network infrastructure provider and the affected local community. The model is aimed at providing comprehensive operational, economic and environmental criteria for location evaluation decisions pertinent to every stakeholder involved.**

I. Introduction

INTERMODAL freight transportation is defined as a system that carries freight from origin to destination by using two or more transportation modes. Intermodal freight transport has become more motivating in the recent years since an increasing demand of road transport creates threats of traffic congestion, fuel depletion, and air quality impacts. In Australia, the government puts its effort to encourage a modal shift of freight transport from road to rail. Establishing a basic infrastructure, especially intermodal terminals or hubs, is one of the most crucial tasks as their locations have direct and indirect impacts for several freight actors. The latter include hub users, hub operators, infrastructure providers, train operators and the affected local community.

A number of researchers have applied exact techniques and network models to determine the optimum number, size, and location of hubs, as well as the overall performance of the system. A comprehensive literature review regarding to the optimization techniques for intermodal freight hub location is available in [1]. Although, the models developed to date attempt to replicate the most of hub user cost characteristics in detail, such as the effect of freight consolidation, scale economies and efficiency threshold, they still have limitations [2]. For example, capacity constraints on the hubs and rail services, frequency of the rail services, time-of-day and seasonal effects on freight flow are all issues that can be solved by using a simulation model. Operational issues tend to be neglected. For example, container double lifting when an immediate lift is not possible at the time of arrival, as well as dwelling time at the hub or the effect of varying truck and container configurations (e.g. number of containers per truck or container sizes). In light of the economic evaluation, cost of travel time reliability or delay cost, which is one of the most important components of freight transport cost, is still largely neglected. In addition, threshold freight volume to ensure the commercial sustainability of the hub is not fully introduced [3]. Finally, externalities are not included in most of the previous research studies.

This paper presents an evaluation model for the location decisions of road-rail intermodal freight (container) hub. It includes model development and discussion for future research investigation. The study is aimed at developing the improved and more comprehensive model to incorporate all of the operational, economic and environmental aspects of every stakeholder involved in the intermodal freight hub location decision problem.

II. Model Development

A. Model Concept

A concept of multi-objective evaluation model for the location decisions of road-rail intermodal freight hub is illustrated in Fig. 1

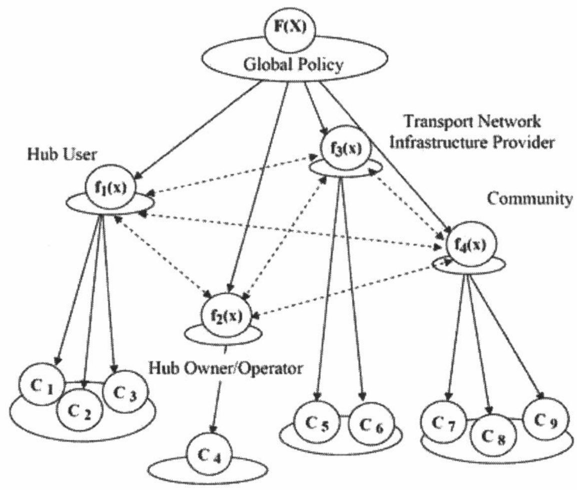

Fig. 1. Multi-objective evaluation model for the location decisions of road-rail intermodal freight hub.

The multi-objective evaluation model is established to determine if the hub location option mutually satisfies every player. The model is classified into three levels. The first level deals with the evaluation of individual objective functions, the second level deals with interaction and negotiation among the players, and the third level deals with global objective function and policy maker. This paper will focus only on the development of the first level of the model.

A concept of intermodal freight transportation is illustrated

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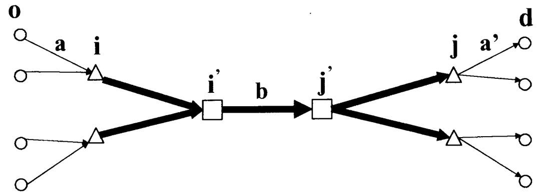
A. Sirikijpanichkul is with Queensland University of Technology, P. O. Box 2434, Brisbane, QLD 4001 Australia (phone: 617-3864-1542; fax: 617-3864-1515; e-mail: a.sirikijpanichkul@student.qut.edu.au).

L. Ferreira is with Queensland University of Technology, P. O. Box 2434, Brisbane, QLD 4001 Australia (e-mail: l.ferreira@qut.edu.au).

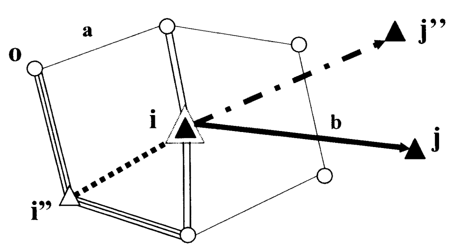
in Fig. 2. Whereas a concept of new and upgraded intermodal hub and transport network infrastructure is shown in Fig. 3.



Legend:

o, d	Freight origin and destination, where, o∈O, ∀o and d∈D, ∀d
i, j	Road–rail intermodal freight hub, where, i∈I, ∀i and j∈J, ∀j
i', j'	Intermediate rail-rail transfer point (if necessary), where, i'⊂ I, ∀i' and j'⊂ J, ∀j'
a, a'	Road link, where, a∈A, ∀a and a'∈A', ∀a'
b	Line-haul rail link, where, b∈B, ∀b

Fig. 2. A concept of Intermodal freight transportation.



Legend:

Existing road link
Proposed upgraded road link (hub access)
Proposed new road link (hub access)
Existing rail link
Proposed new rail link
Proposed upgraded rail link

Existing hub
Proposed new hub
Proposed expanded hub
i'', j'' Adjacent hub to hub i and hub j, where i''⊂ I, ∀i'' and j''⊂ J, ∀j'', respectively.

Fig. 3. A concept of new and upgraded intermodal hub and transport network infrastructure

B. Definition of Terms:

The definition of all the terms used in this paper is listed in Table 1.

TABLE I
DEFINITION OF TERMS

Symbol	Description	Unit
Decision variable:		
x	vector of location choices of candidate intermodal hubs	-
X	feasible sets of vector X	-
Objective function:		
$f_1(x)$	hub user	\$
$f_2(x)$	hub owner or operator	\$
$f_3(x)$	transport network infrastructure provider	\$
$f_4(x)$	community	\$

TEU = twenty foot equivalent unit, km(s)=kilometer(s), hr(s) = hour(s)

TABLE I (CONTINUED)
DEFINITION OF TERMS

Symbol	Description	Unit
Input::		
ϖ	threshold hub freight volume for commercial sustainability e.g. 40 TEU's/day [3]	TEU's/day
Variable:		
where under hub location pattern x,		
$c_1(x)$	total truck transportation cost on road access from origin o to hub i and hub j to destination d	\$
$c_2(x)$	total user hub operating cost at hubs i and j	\$
$c_3(x)$	total line-haul rail transportation cost from hub i to hub j	\$
$c_4(x)$	total cost of hub capital and operating costs	\$
$c_5(x)$	total road network capital cost	\$
$c_6(x)$	total rail network capital cost	\$
$c_7(x)$	total air pollution cost generated by truck	\$
$c_8(x)$	total air pollution cost generated by rail	\$
$c_9(x)$	total air pollution cost generated by hub activities	\$
the following variables are applicable for trucks traveling from origin o to hub i and from hub j to destination d, respectively,		
$TC^t_{oi}(x), TC^t_{jd}(x)$	total truck operating cost	\$
$TT^t_{oi}(x), TT^t_{jd}(x)$	total truck travel-time cost	\$
$TR^t_{oi}(x), TR^t_{jd}(x)$	total truck travel-time reliability cost	\$
$q^t_{oi}(x), q^t_{jd}(x)$	total truck traffic flow	vehicles/hr
$p(q^t_{oi}(x)), p(q^t_{jd}(x))$	percentage of truck carrying two containers	-
$w^t_{oi}(x), w^t_{jd}(x)$	net standard twenty foot equivalent unit of freight	TEU's
$s_i(x), s_j(x)$ $s^t_{oi}(x), s^t_{jd}(x)$	conversion factor from containers to TEU's of freight	TEU's/ container
the following variables are applicable for rail traveling from hub i to hub j,		
$TC^r_{ij}(x)$	total rail operating cost	\$
$TT^r_{ij}(x)$	total rail travel-time cost	\$
$TF^r_{ij}(x)$	total rail-rail transfer cost	\$
$TR^r_{ij}(x)$	total rail travel-time reliability cost	\$
$w^r_{ij}(x)$	net standard twenty foot equivalent unit of rail freight	TEU's
$q^r_{ij}(x)$	total rail freight flow	containers
the following variables are applicable for freight operation at hubs i and j, respectively,		
$\eta_i(w_i(x), \Delta_i(x))$, $\eta_j(w_j(x), \Delta_j(x))$	average unit cost (hub capital and operating costs) per TEU of freight operated at a hub	\$/TEU
$w_i(x), w_j(x)$	freight demand at a hub	TEU's
$\phi_i(x), \phi_j(x)$	existing capacity of a hub	TEU's
$\Delta_i(x), \Delta_j(x)$	difference between freight demand and existing capacity of a hub	TEU's
$LC_i(x), LC_j(x)$	total container lifting cost at a hub	\$
$SC_i(x), SC_j(x)$	total container storage cost at a hub	\$
$WC_i(x), WC_j(x)$	total cost of truck waiting time at a hub	\$

TEU = twenty foot equivalent unit, km(s)=kilometer(s), hr(s) = hour(s)

C. Objective Functions and Constrains:

An objective function has been developed for every freight actor including a hub user, a hub owner or operator, a transport network infrastructure provider, and the community, together with a global objective function as in (1). Please note that all of the following terms conform to the definition of terms in Table 1.

$$\min_{x \in X} F(x) = f_1(x) + f_2(x) + f_3(x) + f_4(x) \tag{1}$$

1) Hub User: The aim is to minimize a total cost of truck transportation cost on road access, user hub operating cost, and line-haul rail transportation cost as in (2).

$$\min_{x \in X} f_1(x) = c_1(x) + c_2(x) + c_3(x) \tag{2}$$

1.1) Truck Transportation Cost incorporates not only truck operating and truck travel-time costs but also truck travel-time reliability cost as in (3).

$$\begin{aligned} c_1(x) &= TC^t_{oi}(x) + TT^t_{oi}(x) + TR^t_{oi}(x) + TC^t_{jd}(x) \\ &+ TT^t_{jd}(x) + TR^t_{jd}(x) \end{aligned} \tag{3}$$

-- *Truck operating cost* is a total of truck operators' out-of-pocket costs which are subject to traffic flow, speed, and total road distance traveled,

-- *Truck travel-time cost* (or value of time) is subject to traffic flow and total truck travel time which relates to traffic flow and capacity of the link. A speed-flow relationship of which the link specific constants comply with Australian road conditions is required for this study [4],

-- *Truck travel-time reliability cost* (or delay cost) is subject to traffic flow and total truck delay time.

Value of time and delay cost of truck are derived indirectly from the approaches and results of previous research in Australia and readjusted to fit the study purpose [5], [6]. For details, please see [7]. These values need to be employed with caution as they vary in a wide range according to several factors e.g. freight value, activity in a supply chain, etc.

1.2) User Hub Operating Cost is a combination of container lifting cost, container storage cost, and cost of truck waiting time at a hub as in (4).

$$\begin{aligned} c_2(x) &= LC_i(x) + SC_i(x) + WC_i(x) + LC_j(x) \\ &+ SC_j(x) + WC_j(x) \end{aligned} \tag{4}$$

As trucks arriving at the hub carry various sizes of containers, conversion from standard container sizes (e.g. 20, 40, 48, 53-foot) to twenty foot equivalent unit (TEU) is necessary. The effect of trucks carrying more than one container is also taken into consideration.

-- Calculation of *container lifting cost* takes into account the trucks carrying more than one container and multi-lifting effects. Multi-lifting happens when an immediate lifting is not possible at the time of arrival.

-- *Container storage cost* relates directly to container dwelling time in a hub commonly represented in a user-defined probabilistic distribution (e.g. Erlang distribution).

-- *Cost of truck waiting time* is equivalent to a total cost of container lifting time.

1.3) Line-haul Rail Transportation Cost includes rail operating cost, rail travel-time cost, rail-rail transfer cost, and rail travel-time reliability cost as in (5).

$$c_3(x) = TC^r_{ij}(x) + TT^r_{ij}(x) + TF^r_{ij}(x) + TR^r_{ij}(x) \tag{5}$$

-- *Rail operating cost* is a total of rail operators' out-of-pocket costs which are subject mainly to rail speed and total rail distance traveled,

-- *Rail travel-time cost* (or value of time) and *Rail travel-time reliability cost* (or delay cost) are subject mainly to total rail travel time and delay time. They are derived indirectly from the approaches and results of previous research and adapted to fit the study purpose [8] – [10].

Subject to the following flow constraints, as in (6),

$$\begin{aligned} &\sum_o \sum_i q^t_{oi}(x) \cdot (1 + p(q^t_{oi}(x))) = \\ &\sum_o \sum_i \sum_j \{(s_i(x) / s^t_{oi}(x)) + q^r_{ij}(x)\} \end{aligned} \tag{6}$$

2) Hub Owner or Operator: The aim is to minimize a total cost of hub capital and operating costs as in (7). The former relates directly to difference between freight demand and existing capacity of a hub (hub expansion) whereas the latter relates to net standard twenty foot equivalent unit of freight operated at a hub. Equation (7) is also applicable to the freight operation at hub j.

$$\min_{x \in X} f^i_2(x) = c_4 = \sum_i w_i(x) \cdot \eta_i(w_i(x), \Delta_i(x)) \tag{7}$$

Subject to flow constraints of (8), commercial sustainability constraint of (9) and capacity constraints of (10) – (12),

$$w_i(x) = \sum_o w_{oi}(x), \forall i \tag{8}$$

$$w_i(x) \geq \varpi, \forall i, j \tag{9}$$

$$\sum_i (\phi_i(x) + \Delta_i(x)) \geq \sum_i w_i(x), \forall i, x \tag{10}$$

where,

$$\Delta_i(x) = w_i(x) - \phi_i(x) \quad \text{if} \quad w_i(x) > \phi_i(x), \forall i, x \tag{11}$$

$$\Delta_i(x) = 0 \qquad \text{if } w_i(x) \leq \phi_i(x), \forall i, x \tag{12}$$

Constraints (8) – (12) are also applicable to the freight operation at hub j.

3) Transportation Network Infrastructure Provider: The aim is to minimize a total capital cost of road and rail network. Capital cost of road network incorporates capital cost of new and upgraded road links whereas capital cost of rail network incorporates capital cost of new and upgraded rail links. As these costs can be defined easily and straightforwardly, only the simplified objective is provided in (13) assuming the entire proposed new and upgraded road links and rail links are of the same standard. The concept of new and upgraded intermodal hub and transport network infrastructure is shown in Fig. 3.

$$\min_{x \in X} f_3(x) = c_5(x) + c_6(x) \tag{13}$$

4) Community: The aim is to minimize a total externality generated by hub activities. This study will concentrate on air pollution including Nitrogen Oxide, Sulfur Dioxide, Volatile Organic Compound, and Suspended Particulate Matter, which contributes significantly to the social costs of the community. The community cost includes air pollution cost generated by truck, rail, and hub activities, as in (14). Only the simplified objective function is provided in this paper as the problem of quantifying air quality impacts have already been investigated by a number of studies as reviewed by [11].

$$\min_{x \in X} f_4(x) = c_7(x) + c_8(x) + c_9(x) \tag{14}$$

III. Model Testing and Validation

To assure that the model is calibrated and validated, it will be tested with a real-world case study. In this research, the potential sites of intermodal freight terminals in South East Queensland, according to the Stage 2 of South East Queensland Inter-modal Freight Terminals Study (SEQIFTS) report will be used as a case study [12]. The model will be calibrated and validated against a set of validation data.

An initial location analysis has been undertaken by using a hypothetical case of 20 demand zones and 9 potential candidate sites for the intermodal hubs in the study area. Two steps of analysis are processed, namely;

-- *1st Step: Integer Programming* applying set-covering problems and if-then constraints to determine an approximate location of the hubs [13]; and

-- *2nd Step: P-Median Problem* to find the exact location of the hubs in a Cartesian coordinate system by minimizing the sum of the weighted distance between the demand nodes and the hubs [14].

IV. Discussion for Further Research

The developed model is aimed at optimizing the objective function of individual stakeholder of intermodal freight hub location decisions. The following issues need to be addressed in future research.

A. Evaluation Techniques

The exact model as presented in this paper provides components of the evaluation models, especially in the freight operational aspects. The computation time to find the exact solutions is nevertheless relatively long in comparison with other advance techniques including heuristics or meta-heuristics as reviewed by [1]. Different evaluation techniques should be compared regarding to their performance and computation time.

B. Multi-objective Evaluation and Negotiation Implication

It is idealistic to find a solution that satisfies every stakeholder. Further model development will focus on one the multi-objective evaluation and negotiation process. Some advance techniques such as multi-agent systems, as reviewed by [15]-[17], are capable of simulating a social dynamic interaction, may be appropriate and useful to handle this type of problem.

C. Valuation of Community Impacts

Although there are evidences showing monetary values of community impacts or externalities. It is still controversial of the reliable values and consequently requires a close attention when used. To avoid such skeptical use, fuzzy logic can be employed to reduce the unreliability of the data [18].

D. Other Applications

A number of studies introduce an application of simulation models. However, most of them attempt to optimize the activities inside the hub [19]. The range of approaches should be broadened to cover other applications such as hub access traffic simulation models.

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